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## DESCRIPTION

REFLECTIVE LIQUID CRYSTAL DEVICES

## 5 TECHNICAL FIELD

The present invention relates to reflective liquid crystal devices and more particularly to reflective liquid crystal display devices comprising a bistable twisted nematic (BTN) liquid crystal.

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## BACKGROUND ART

Reflective liquid crystal devices typically comprise a linear polariser and a mirror, with one or more retarders and a switchable liquid crystal element sandwiched between the polariser and the mirror. In a first state of the liquid crystal element, linearly polarised light passing through the polariser is reflected from the mirror and arrives back at the polariser with the same linear polarisation. Hence the reflected light is transmitted by the polariser and the device appears in the bright state. In a second state of the liquid crystal element, linearly polarised light is converted to have a circular polarisation such that upon reflection at the mirror the "handedness" of the circular polarisation is changed (i.e. from right to left or from left to right). Light arriving back at the polariser is arranged to have a polarisation angle  $90^\circ$  shifted from the axis of the polariser (either the transmission or the absorption axis of the polariser may be considered and both give identical results). Hence, the reflected light is not transmitted by the polariser and the device appears in the dark state. Reflective liquid crystal devices are attractive particularly for

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low power consumption applications.

5 GB9622733.5 describes a reflective liquid crystal display device comprising a polariser and a mirror between which are disposed several retarders. One of the retarders is a liquid crystal element whose optic axis is switchable so as to switch the device between a reflective state and a non-reflective state.

10 EP0018180 describes a liquid crystal cell comprising a cholesteric liquid crystal. The liquid crystal is bistable and can exist in either one of its two metastable states until specific steps are taken to cause a transition to the other metastable state. Energy is  
15 expended only when a transition occurs.

The article "Bistable Twisted Nematic Mode with One Polariser for Reflective Liquid Crystal Displays", Kim, Yu & Lee, IDRC Asia Display 98, Seoul, Korea, p 763,  
20 describes a device having in sequence an input linear polariser, a quarter wave retarder, a BTN element, and a mirror.

The article "Reflective Bistable Twisted Nematic Liquid Crystal Display", Xie & Kwok, Jpn J. Appl. Phys, Vol37, part 1, No. 5a (1998), p 2572, describes a device  
25 having an input polariser, a BTN mode and a reflector. The proposed device does not include any additional retarders and states that the contrast ratio measured is  
30 about 6:1.

WO98/48320 describes a reflective liquid crystal display device comprising a polariser and a mirror between

which are disposed a half wave retarder, a quarter wave retarder, and a liquid crystal element.

Abstract 39.3 (published in the SID 1999  
5 International Symposium, Seminar & Exhibition -Advance  
program, in advance of a conference to be held in San Jose,  
CA, USA, May 16-21 1999) titled "Reflective Single-  
Polariser Bistable Nematic LCD with Optimum Twist", Y.J.  
Kim & J.S. Patel, describes a single-polariser reflective  
10 LCD having a bistable twisted nematic mode. The twist  
angles of the two bistable states are  $63.6^\circ$  and  $423.6^\circ$ .

The article "Fast bistable nematic display using  
monostable surface switching", I. Dozov, M. Nobili and  
15 G. Durand, Appl. Phys. Lett. 70 (9), 3 March 1997, de-  
scribes a device having a two bistable states, namely a  
metastable uniform (untwisted) state and a half-turn  
( $180^\circ$ ) twist state.

## 20 DISCLOSURE OF THE INVENTION

According to a first aspect of the present  
invention there is provided a reflective liquid crystal  
device comprising in sequence a linear polariser, a  
retarder arrangement comprising two retarders, and a  
25 reflector, wherein, in at least one state of the device,  
a first of said retarders acts to rotate linearly  
polarised light of wavelength  $\lambda$ , and a second of the  
retarders acts to convert linearly polarised light of  
wavelength  $y\lambda$  ( where  $0.7 < y < 1.3$ ) to substantially  
30 circular polarised light, and wherein at least one of the  
said first and second retarders comprises a Bistable  
Twisted Nematic (BTN) liquid crystal.

The wavelength  $\lambda$  is an operating wavelength of the reflective liquid crystal device and lies in the visible spectrum and is preferably in the range 400-700nm, more preferably 420-600nm, and more preferably still in the region 440-550nm. Most preferably  $\lambda$  is approximately 550nm.

Preferably, the retarder comprises a BTN liquid crystal providing a retardation of  $n\lambda/4$ .

According to a second aspect of the present invention there is provided a reflective liquid crystal device comprising in sequence a linear polariser, a retarder arrangement comprising two retarders, and a reflector, wherein a first of said retarders provides a retardation of substantially  $m\lambda/2$  and a second of the retarders provides a retardation of substantially  $n\lambda/4$  where  $m$  is an integer and  $n$  is an odd integer, and wherein at least one of the said first and second retarders comprises a Bistable Twisted Nematic (BTN) liquid crystal and is switchable between a first state in which the retarder provides a retardation of substantially  $m\lambda/2$  or  $n\lambda/4$  and a second state in which the retardation is substantially zero.

According to a third aspect of the present invention there is provided a reflective liquid crystal device comprising in sequence a linear polariser, a retarder arrangement comprising at least three retarders, and a reflector, wherein at least one of said retarders comprises a Bistable Twisted Nematic (BTN) liquid crystal and is switchable between first and second retardation states.

The wavelength  $\lambda$  is an operating wavelength of the reflective liquid crystal device and lies in the visible spectrum and is preferably in the range 400-700nm, more preferably 420-600nm, and more preferably still in the region 440-550nm. Most preferably  $\lambda$  is approximately 550nm.

Preferably, the retarder comprising a BTN liquid crystal providing a retardation in said first state of substantially  $m\lambda/2$  or  $n\lambda/4$  where  $m$  is an integer and  $n$  is an odd integer, and a retardation in said second state of substantially zero. The others of said retarders may provide a retardation of substantially  $m\lambda/2$  or  $n\lambda/4$ .

"Optic axis" means slow optic axis.

#### BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the present invention and in order to show how the same may be carried into effect reference will now be made, by way of example, to the accompanying drawings, in which:

Figure 1 is a reflectance versus wavelength plot - maximum luminance attainable by the system;

Figure 2 is a reflectance versus wavelength plot - minimum luminance attainable by the system;

Figure 3 shows LC configurations for which LC behaves equivalently to an untwisted  $\frac{1}{2}$  wave plate retarder ( $\theta(\phi)$  = angle of the input director of LC with respect

to the incident linear polarisation direction,  $\phi$  = twist of LC layer,  $\Delta n \cdot d / \lambda$  specifies the required  $\Delta n \cdot d / \lambda$  for which the LC device behaves like a  $\frac{1}{2}$  wave plate retarder);

5           Figure 4 is a schematic representation of single polariser reflective configuration with a single retarder (BTN), LC configurations from table in Figure 3;

10           Figure 5 shows contrasts calculated as a function of  $\Delta n \cdot d / \lambda$  for the configurations described in Figure 4 and Figure 3 where the high twist state satisfies ( $\phi + 360^\circ$ );

15           Figure 6 shows a luminous reflectance versus wavelength plot for the configuration providing the highest contrast described by configuration in Figure 4, low twist dark state;

20           Figure 7 shows a single retarder (BTN) in single polariser reflective configuration described in prior art by Xie & Kwok in Jpn. J. Appl. Phys, Vol37, part 1, No. 5a (1998), p 2572;

25           Figure 8 shows a luminous reflectance versus wavelength plot for the configuration shown in Figure 7, high twist dark state;

30           Figure 9 shows a two-retarder configuration described in prior art by Kim, Yu & Lee at IDRC Asia Display 98;

          Figure 10 shows a luminous reflectance versus wavelength plot for the configuration shown in Figure 9, high twist dark state.

Figure 11 shows a two-retarder configuration in reflection described in Embodiment 1(a);

5           Figure 12 shows a luminous reflectance versus wavelength plot for the configuration shown in Figure 11, untwisted dark state;

10           Figure 13 shows a two-retarder configuration in reflection described in Embodiment 1(b);

15           Figure 14 shows a luminous reflectance versus wavelength plot for the configuration shown in Figure 13, untwisted dark state;

            Figure 15 shows a two-retarder configuration in reflection described in Embodiment 2;

20           Figure 16 shows a luminous reflectance versus wavelength plot for the configuration shown in Figure 15, low twist dark state;

25           Figure 17 shows a luminous reflectance versus wavelength plot for the configuration shown in Figure 15; A retarder and LC thickness reduction of 30% provides the improved contrast;

30           Figure 18 shows a two-retarder configuration in reflection with an internal retarder described in Embodiment 3;

            Figure 19 shows a luminous reflectance VS wavelength plot for the configuration shown in Figure 18,

untwisted dark state;

Figure 20(a) shows a two-retarder configuration in reflection described in Embodiment 4(a);

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Figure 20(b) shows a two-retarder configuration in reflection described in Embodiment 4(b);

Figure 20(c) shows a two-retarder configuration in reflection described in Embodiment 4(c);

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Figure 21 shows a luminous reflectance versus wavelength plot for the configuration shown in Figure 20(a);

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Figure 22 shows a luminous reflectance VS wavelength plot for the configuration shown in Figure 20(b);

Figure 23 shows a luminous reflectance versus wavelength plot for the configuration shown in Figure 20(c);

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Figure 24 shows a two-retarder configuration reflection described in Embodiment 5,  $\theta_1$  varied;

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Figure 25 shows a luminous reflectance values of the dark state given by the low twist metastable state  $\phi$ , as a function of  $\theta_2$  (from  $0^\circ$  to  $360^\circ$ );

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Figure 26 shows a contrast plot obtained as a function of  $\theta_1$  (angle between polariser and half-wave retarder, see Figure 24) from  $0^\circ$  to  $90^\circ$ ;



Figure 27 shows a luminous reflectance versus wavelength plot for  $\theta_1=6^\circ$ , Embodiment 5;

5 Figure 28 shows a luminous reflectance versus wavelength plot for  $\theta_1=84^\circ$ , Embodiment 5;

10 Figure 29 shows a two-retarder configuration in reflection described in Embodiment 6,  $d$ ,  $\theta$  and  $\phi$  are varied;

Figure 30 shows a contrast plot as a function of  $\Delta n \cdot d / \lambda$ , for each  $d$  the optimum  $\theta$  and  $\phi$  are found;

15 Figure 31 shows a Luminous reflectance versus wavelength plot for  $\Delta n \cdot d / \lambda = 0.25$ ,  $d=2\mu\text{m}$ , Embodiment 6;

Figure 32 shows a three-retarder configuration in reflection described in Embodiment 7;

20 Figure 33 shows a luminous reflectance versus wavelength plot for configuration shown in Figure 32. Untwisted state provides the dark state;

25 Figure 34 shows a three-retarder configuration in reflection, described in Embodiment 8,  $d=2\mu\text{m}$ ;

30 Figure 35 shows a luminous reflectance versus wavelength plot for configuration shown in Figure 34. Untwisted state provides the dark state;

Figure 36 shows a three-retarder configuration in reflection described in Embodiment 9,  $d=2.56\mu\text{m}$ ;

5        Figure 37 shows a luminous reflectance versus wavelength plot for configuration shown in Figure 36; untwisted state provides the dark state, the bright state  $\phi+180^\circ$  twist state and  $\phi\pm 360^\circ$  twist states are also plotted;

10        Figure 38 shows a three-retarder achromatic configuration in reflection described in Embodiment 10,  $d=2\mu\text{m}$ ;

15        Figure 39 shows a luminous reflectance versus wavelength plot for configuration shown in Figure 38. High twist state provides the dark state;

20        Figure 40 shows a three-retarder achromatic configuration in reflection described in Embodiment 11; the LC orientation  $\theta$  and twist  $\phi$  are determined for different thickness LC layers. High twist state provides the dark state;

25        Figure 41 is a contrast plot shown as a function of  $\Delta n \cdot d / \lambda$ , for each  $d$  the optimum  $\theta$  and  $\phi$  are found;

30        Figure 42 is a luminous reflectance versus wavelength plot for  $\Delta n \cdot d / \lambda = 0.25$ ;

      Figure 43 is a luminous reflectance versus wavelength plot for  $\Delta n \cdot d / \lambda = 0.72$ ; and

      Figure 44 is a luminous reflectance versus wavelength plot for  $\Delta n \cdot d / \lambda = 0.536$ .

#### BEST MODE FOR CARRYING OUT THE INVENTION

A Bistable Twisted Nematic (BTN) mode used in a reflection configuration requires one of its two metastable states, i.e. addressable states ( $\phi$  &  $\phi \pm 360^\circ$ ), to provide a dark state and the other a bright state. A single retarder layer (i.e. BTN only) does not provide a good achromatic dark state when used with one polariser in reflection (demonstrated below). Configurations involving several retarder layers are required when seeking good achromatic dark states that switch to good bright states.

The likelihood of the undesired stable state  $\phi \pm 180^\circ$  nucleating into an addressed pixel means that its optical appearance (luminance, colour co-ordinates, etc.) may be of importance. It has been found that the stable state  $\phi \pm 180^\circ$  bears a closer resemblance optically to the high twist metastable state than to the low twist (or untwisted) metastable state, i.e. the reflection spectra of the ( $\phi \pm 360^\circ$ ) state is very similar to that of the ( $\phi \pm 180^\circ$ ) state.

The Embodiments to be described below provide the option of selecting which of the BTN metastable twist states will provide the dark state and which the bright states, for example in Embodiments 4 & 6 the low twist state gives the dark state and in Embodiment 11 the high twist state gives the dark state. It may be advantageous to select the high twist state to provide the "background" state for the display. By "background" state we refer to the state (dark or bright) that covers a greater percentage of the display over both space and time. For example, in an electronic book, black text would appear

on a white background to mimic printed paper, and as a result a large percentage of the display, say approximately 70%, would show white. So, for an electronic book the high twist state would be selected to provide the white state, i.e. the "background" state, so that if any of the undesired twist states ( $\phi \neq 180^\circ$ ) did nucleate or remained in the inter-pixel (electrode) gaps (which may be the case if the gaps are very large and the LC is not switched within them) it would be less noticeable to the observer, with less of a detrimental effect on the contrast, than had the low twist  $\phi$  state been selected to provide the "background" state.

Alternatively, a black mask can be used to mask-off the inter-pixel (electrode) gaps in the case where the LC within these gaps is not switched out of the undesired ( $\phi \neq 180^\circ$ ) twist state by the application of a field during addressing.

Due to the similarity of the reflection spectra for the ( $\phi \neq 360^\circ$ ) and the ( $\phi \neq 180^\circ$ ) twist states (see Embodiment 9 below), those skilled in the art can apply this invention to the bistable device described by I. Dozov, M. Nobili and G. Durand, Appl. Phys. Lett. 70 (9), 3 March 1997.

In addition to the bright, high contrast requirements for reflection displays, the thickness of the LC layer has to be compatible with fabrication processes. A low birefringence ( $\Delta n$ ) LC material provides a thicker LC layer, though it is also possible to increase the LC layer thickness by introducing a small amount of twist into the layer to compensate for the extra thickness

(this may modify the resulting optics). Alternatively, if the fabrication requires a thinner LC layer, a higher birefringence ( $\Delta n$ ) LC material can be used.

5           Various    BTN    mode    configurations    were  
investigated by numerical modelling for their use in  
reflection displays. Being a reflective display the  
luminous reflectance of the bright state will depend on  
the light source utilised. In the examples given below,  
10   a CIE standard illuminant D-65 was used. Dispersion was  
included in all the modelled elements:  $2\mu\text{m}$  thick aluminium  
reflector;  $2.5\mu\text{m}$  polariser;  $50\mu\text{m}$  retarders and LC layer.  
The low birefringence ( $\Delta n=0.0685$  at  $20^\circ\text{C}$ ) liquid crystal  
MJ96538 (Merck Japan) was used in zero surface tilt  
15   configurations, with uniform twist profiles at zero  
applied field. (nb. Introducing a surface tilt may  
modify some of these results slightly).

20           The maximum contrast ratio ( $\text{CR}=\text{L}_{\text{MAX}}/\text{L}_{\text{MIN}}$ ) attain-  
able for a single polariser reflective system for the  
above-mentioned elements was calculated to be 169. The  
maximum luminance ( $\text{L}_{\text{MAX}}$ ) results from the polariser-  
reflector configuration (no LC or retarders), and the  
minimum luminance ( $\text{L}_{\text{MIN}}$ ) is obtained by adding a perfect  
25   (theoretical) quarter-wave retarder, i.e. quarter wave  
retarder at all wavelengths between the polariser and  
reflector, oriented at  $45^\circ$  to either the transmission or  
the absorption axis of the polariser. The luminous  
reflectance curves for this maximum (bright state) and  
30   minimum (dark state) luminances are shown in Figures 1  
and 2. The dark state is very achromatic in behaviour  
while the bright state is governed both by the "shape"  
of the D65 light source and the polariser transmission

spectrum.

The embodiments of the invention to be described aim to obtain high contrast in reflection in various BTN configurations by means of achromatic dark states (dark over a wide range of wavelengths, preferably covering all the visible range) which switch to good bright states. Achromaticity of the dark and bright states is desired so that the display does not appear coloured.

The configurations constituting a single polariser reflective device consisting of a single (BTN) retarder and the configurations described in the prior art were modelled for comparative purposes. This was done using the elements as described previously, though suitably adjusted to match those described in the prior art.

The single polariser reflective configurations consisting of a single BTN retarder positioned between the reflector and the polariser require that the LC layer behave equivalently to an untwisted  $\frac{1}{2}$  wave plate where the low twist provides the dark state. The LC configurations, i.e. the retardation  $\Delta n \cdot d / \lambda$  ( $\Delta n$ =birefringence,  $d$ =thickness,  $\lambda$ =wavelength), twist  $\phi$  and angle  $\theta(\phi)$  of the input director of LC with respect to the incident linear polarisation direction) that satisfy this requirement are listed in the table in Figure 3, covering a thickness range from  $2\mu\text{m}$  to  $6\mu\text{m}$  ( $\Delta n \cdot d / \lambda$  from 0.25 to 0.75 for LC MJ96538). The schematic representation of these configurations are provided in Figure 4; the BTN mode placed between the polariser and reflector at an orientation ( $\theta(\phi)$ ) to the transmission

axis of the polariser. A dark state is obtained when the LC layer corresponds to a  $\frac{1}{2}$ -wave or  $\frac{3}{2}$ -wave retarder placed at  $45^\circ$  to the transmission axis of the polariser. The bright state corresponds to the high twist state ( $\phi \pm 360^\circ$ ). The contrast was calculated for each of the cases listed in table 3 where the high twist state corresponded to the ( $\phi + 360^\circ$ ) and plotted as a function of  $\Delta n \cdot d / \lambda$ , in Figure 5. Utilising the ( $\phi - 360^\circ$ ) state for the bright state instead of the ( $\phi + 360^\circ$ ) only changed the resulting contrast by a maximum of 1%, while for some cases it gave an identical contrast. The contrast does not decrease drastically until  $\Delta n \cdot d / \lambda > 0.4$  ( $d > 3.2 \mu\text{m}$ ). The highest contrast (CR=40) obtained was for a cell thickness of  $2 \mu\text{m}$ , untwisted LC layer,  $\theta(\phi) = \pm 45^\circ$ ; though at a thickness of  $2.8 \mu\text{m}$ ,  $\phi = -63.6^\circ$  and  $\theta(\phi) = 0^\circ$  the contrast has only decreased to 39. Figure 6 shows the luminous reflectance as a function of wavelength for the dark and bright states of the highest contrast configuration ( $d = 2 \mu\text{m}$ ,  $\phi = 0^\circ$ ,  $\theta(\phi) = \pm 45^\circ$ ). The dark states of all the configurations described in the table in Figure 3 are chromatic and become more so as the thickness of the LC layer increases (wavelength range over which there is a minimum reflectance reduces from 40nm to 25nm).

The configuration described by Xie & Kwok in Jpn. J. Appl. Phys, Vol37, part 1, No. 5a (1998), p 2572, is represented schematically in Figure 7. The high twist state provides the dark state; LC layer thickness  $13.7 \mu\text{m}$ ,  $\phi = -36^\circ$  oriented parallel to the transmission axis of the polariser. The resulting luminous reflectance curves, shown in Figure 8, gave a very chromatic dark state leading to a contrast ratio of ~6. IDRC Asia Display 98 by Kim, Yu & Lee is represented in Figure 9;  $2.9 \mu\text{m}$  LC layer

thickness,  $\phi=0^\circ$  oriented at  $45^\circ$  to the transmission axis of the polariser. A 140nm retarder positioned between the polariser and BTN was either at  $45^\circ$  or  $135^\circ$  to the transmission axis of the polariser and depending on the  
5 retarder's orientation the resulting contrast was either ~13 or ~17. The resulting luminous reflectance curves are shown in Figure 10.

As can be seen, both the prior art and the single  
10 polariser reflective configurations with a single retarder (BTN) give low contrasts with chromatic dark states, compared to the maximum attainable contrast of 169.

The following configurations described in the  
15 embodiments are mostly examples of the LC layer acting as a switchable retarder located adjacent to the reflector. This set up aids fabrication purposes; i.e. no internal retarders are required in the device as they can be located externally. Two and three retarder configurations are  
20 investigated. In most of the embodiments discussed, any of the other retarder elements described in the configurations can be substituted by a LC layer so long as it adopts the correct retardation and orientation.

25 The configurations investigated obtain the dark state by converting linearly polarised light generated by the polariser into circularly polarised light. One of the BTN metastable states contributes to the conversion to circularly polarised light while the other metastable  
30 state doesn't. Upon reflection back through the system, a dark and a bright state are obtained. Alternatively, it is possible to convert the linearly polarised light generated by the polariser into elliptically polarised



light by altering the retarder properties, e.g. orientation and/or thickness, such that one of the BTN metastable twist states converts the elliptically polarised light to circular polarised light and the other  
5 metastable twist state converts elliptically polarised light to linear polarised light. Upon reflection back through the system a dark and a bright state are obtained.

Those skilled in the art will be able to vary the  
10 actual values from those in the embodiments and obtain acceptable performance. The tolerance  $\times$  to these changes is of course configuration dependent, e.g. as seen in Figures 30 and 41. In all of the embodiments described below, either the transmission or the absorption axis of  
15 the polariser may be considered and give identical results.

It is noted that for each embodiment to be described, an equivalent can be obtained by changing the  
20 sign of each angle (i.e. by multiplying all the orientation angles of the retarders and LC as well as the LC twist by  $-1$ ).

*Embodiment 1*

25 *Half-wave ( $\lambda/2$ ) retarder + quarter-wave ( $\lambda/4$ ) LC - untwisted dark state ( $\phi=0^\circ$ ).*

(a) Configuration shown in Figure 11: fixed half-wave ( $\Delta n.d=270$ ) retarder at  $15^\circ$  to the transmission  
30 axis of the polariser followed by a quarter-wave ( $\lambda/4$ ) LC layer at  $75^\circ$  to the transmission axis of the polariser. The LC layer is  $2\mu\text{m}$  thick. A dark state which is more achromatic than that of a single retarder layer is

provided by the untwisted state, with a minimum reflectance over ~110nm wavelength range compared to the 40nm wavelength range obtained for the best single BTN layer in single polariser reflective configuration. The  
5 luminous reflectance plot is shown in Figure 12. The bright state is the same for both the +360° and -360° twisted state giving a contrast of 79.5.

In this case the fixed half-wave retarder rotates  
10 linearly polarised light of wavelength  $\lambda = 540\text{nm}$  whilst the quarter-wave LC layer converts light of wavelength  $y \times \lambda$  (with  $y = 1$ ) to circular polarised light. Less ideal, but reasonable, results can be obtained with  $y$  slightly different from 1. Maintaining  $\lambda = 540\text{nm}$  a contrast ratio  
15 of 29 is obtained for  $y = 0.9$  whilst a contrast ratio of 31 is obtained for  $y = 1.1$ . It will be appreciated by those skilled in the art that the value of  $y$  can be optimised depending upon the embodiment and materials used.

(b) The half-wave retarder is placed at 22.5° to the transmission axis of the polariser and the LC layer at 90° to the transmission axis of the polariser, see Figure 13. The LC layer has a thickness of  $2\mu\text{m}$ . The dark state is given by the untwisted state but both states are  
20 shown in Figure 14 to be quite chromatic. A contrast of 38 is obtained for such a configuration.

#### *Embodiment 2*

*Half-wave ( $\lambda/2$ ) retarder + quarter-wave ( $\lambda/4$ ) LC - low twist  $\phi$  provides dark state.*  
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In this case, both BTN states have some degree of twist as a result of using a thicker LC layer ( $d=2.8\mu\text{m}$ ).

The half-wave ( $\lambda/2$ ) ( $\Delta n \cdot d = 270$ ) retarder is at  $15^\circ$  to the transmission axis of the polariser with the LC layer oriented at  $30^\circ$  to the transmission axis of the polariser. A twist of  $\phi = 63.6^\circ$  is incorporated to the LC layer and provides the dark state. The higher twist states ( $\phi \pm 360^\circ$ ) provides the bright state of which the ( $\phi - 360^\circ$ ) =  $-296.4^\circ$  provides the better bright state. A diagram of this configuration is shown in Figure 15. A contrast of 31.6 is obtained. The luminous reflectance curves shown in Figure 16 suggest that the contrast would be higher were the curves shifted to the left. This can be achieved by reducing the thickness of the retarder and LC layer. For example, reducing both their thickness' by 30% resulted in a contrast of 66.5, over twice the previous contrast of 31.6. The luminous reflectance curves are shown in Figure 17.

### *Embodiment 3*

*Half-wave ( $\lambda/2$ ) LC + internal quarter-wave ( $\lambda/4$ ) retarder - untwisted dark state ( $\phi = 0^\circ$ ).*

This configuration is similar to Embodiment 1(a) except that the LC layer acts as the half-wave retarder ( $\Delta n \cdot d = 270$ ) oriented at  $15^\circ$  to the transmission axis of the polariser. The LC layer thickness is  $4\mu\text{m}$ . A fixed quarter-wave retarder ( $\Delta n \cdot d = 132.5$ ) at  $75^\circ$  to the transmission axis of the polariser is located between the LC layer and the reflector, see Figure 18. The dark state corresponds to the untwisted state ( $\phi = 0^\circ$ ) and the high twist state ( $\pm 360^\circ$ ) to the bright state, the  $\pm 360^\circ$  have the same luminous reflectance. The luminous reflectance curves are shown in Figure 19. A contrast of 64.6 is obtained.

5       The incorporation of an internal retarder inside  
a liquid crystal device is not an impractical technique,  
however it does increase the number of fabrication steps  
required.

10       The internal retarder can be fabricated using  
reactive mesogen (RM) materials, for example diacrylate  
RM257 (Merck Ltd, Poole). Reactive mesogens exhibit  
conventional liquid crystalline phases but undergo  
polymerisation under certain conditions, one of which  
being the exposure to ultraviolet light in a nitrogen  
atmosphere as the presence of oxygen inhibits the  
polymerisation reaction. Generally, a photoinitiator is  
15       required as a source of free radicals. Thus in the liquid  
crystalline phase the reactive mesogen can be aligned by  
an aligned alignment layer. The desired retardation can  
be obtained by tuning the spin conditions (layer  
thickness), the concentration of the reactive mesogen  
20       solution, the temperature at curing or a combination of  
all these.

25       The basic structure of the device can for example  
consist of a patterned aluminium (Al) reflector that  
doubles as the electrode, an aligned alignment layer on  
the reflector which aligns a reactive mesogen layer with  
the desired orientation and retardation. A second  
alignment layer can be placed on to the internal retarder.  
The device can be formed by combining this reflector-  
30       substrate with a counter substrate containing a patterned  
transparent patterned electrode, for example Indium tin  
oxide layer (ITO), coated by an (aligned) alignment layer  
to align the BTN LC layer. Additionally, a (patterned)

transparent electrode may be placed on to the internal retarder (between the internal retarder and the alignment layer) in order to reduce the voltage drop that may occur across the internal retarder when using the reflector as the electrode.

#### *Embodiment 4*

*Specific wavelength ( $\lambda/2$ ) retarder + twisted LC configurations - low twist provides the dark state  $\phi$ .*

Three such solutions were investigated and are shown schematically in Figure 20, labelled (a) to (c). The LC layer is twisted through  $\phi$  to give the dark state and the bright state corresponds to the higher twisted case ( $\phi \pm 360^\circ$ ). The optimum bright state was obtained for the ( $\phi - 360^\circ$ ) twist state, providing reasonable contrasts:

(a) An untwisted fixed ( $\Delta n \cdot d = 185\text{nm}$ ) retarder and ( $\Delta n \cdot d = 174\text{nm}$ ,  $d = 2.54\mu\text{m}$ ) LC layer, are both orientated at  $15^\circ$  to the transmission axis of the polariser. The LC has a twist ( $\phi$ ) of  $85.5^\circ$ . This configuration gives a contrast of 87 and the luminous reflectance curves are plotted in Figure 21.

(b) The untwisted fixed ( $\Delta n \cdot d = 221\text{nm}$ ) retarder is orientated at  $15^\circ$  to the transmission axis of the polariser and ( $\Delta n \cdot d = 152\text{nm}$ ,  $d = 2.22\mu\text{m}$ ) LC layer is orientated at  $32.5^\circ$  to the transmission axis of the polariser with an internal twist ( $\phi$ ) of  $63.6^\circ$ . The luminous reflectance curves are plotted in Figure 22 and a contrast of 81 was obtained.

(c) The untwisted fixed ( $\Delta n \cdot d = 208\text{nm}$ ) retarder is orientated at  $14^\circ$  to the transmission axis of the polariser

and ( $\Delta n d = 152 \text{ nm}$ ,  $d = 2.22 \mu\text{m}$ ) LC layer is orientated at  $29^\circ$  to the transmission axis of the polariser with an internal twist ( $\phi$ ) of  $67^\circ$ . The luminous reflectance curves are plotted in Figure 23 and a high contrasts of 99 was obtained.

#### Embodiment 5

*Configurations where the angle ( $\theta_1$ ) between the polariser and LC layer satisfies  $\theta_1 = 2\theta_2$ , where  $\theta_2$  is the angle between the polariser and half-wave retarder - low twist state ( $\phi$ ) provides the dark state.*

These configurations are illustrated in Figure 24: half-wave retarder ( $\Delta n \cdot d = 270$ ) placed between the LC layer and polariser at an angle of  $\theta_1$  to the transmission axis of the polariser and the LC layer is at  $\theta_2$  to the transmission axis of the polariser where  $\theta_1 = 2\theta_2$  (since the half-wave retarder rotates linear polarisation by  $2\theta_1$ ); varying  $\theta_1$  from  $0^\circ$  to  $180^\circ$  (i.e.  $\theta_2$  from  $0^\circ$  to  $360^\circ$ ), and calculating the luminous reflectance curves for the low twist (dark) state as a function of  $\theta_2$  for a LC layer, thickness of  $2.8 \mu\text{m}$  and low twist state of  $\phi = \pm 63.6^\circ$  selected from the table in Figure 3. This LC layer configuration constitutes just one example chosen from the table in Figure 3 and any thickness with its corresponding twist can be chosen and subjected to a similar procedure. A negative  $\phi$  twist requires the values of  $\theta_1$  and all corresponding angles to be reversed in sign. The luminous reflectance values for the low twist state are plotted as a function of  $\theta_2$  in Figure 25. These results indicate that a positive low LC layer twist provides a lower luminance (better dark state) over the  $0^\circ$  to  $180^\circ$  range for  $\theta_2$  than an equivalent negative LC layer twist.

The resulting contrasts were calculated as a function of  $\theta_1$  and shown in Figure 26. Two regions were found to give good contrasts,  $\theta_1 = 6^\circ$  &  $84^\circ$ , with respective contrasts of 50.5 and 59. The luminous reflectance curves for  $\theta_1 = 6^\circ$  are shown in Figure 27, the dark state has a high luminous reflectance at low wavelengths which lowers the overall contrast, even though at higher wavelengths the dark state looks very achromatic. An improved dark state at low wavelengths can be obtained by shifting the curves to the left by reducing the retarder and LC layer thickness as demonstrated in Embodiment 2. The dark state at  $\theta_1 = 84^\circ$  has a lower leakage of light at short wavelengths ( $\lambda < 450\text{nm}$ ) than the dark state at  $\theta_1 = 6^\circ$ , see the luminous reflectance curves in Figure 28, resulting in an overall higher contrast even though the wavelength range over which both these dark states have a minimum transmission of light is the same.

This exercise can be repeated for different retarder and LC layer thickness' (and hence different LC layer twist) to try and improve the contrast and/or increase the LC layer' thickness.

**Embodiment 6**

*Fixed half-wave ( $\lambda/2$ ) retarder + variable thickness LC layer - low twist ( $\phi$ ) provides dark state.*

This arrangement is shown in Figure 29, a half-wave retarder ( $\Delta n \cdot d = 270$ ) at  $15^\circ$  to the transmission axis of the polariser. The LC layer is placed between the retarder and reflector and the low twist state provides the dark state. The thickness of the LC layer

is selected from the table of LC configurations in Figure 3 (between  $\Delta n \cdot d / \lambda = 0.25$  &  $0.75$ ) and for each thickness the configuration (orientation  $\theta$  and twist  $\phi$ ) giving the best dark state was determined via locating the minima on a 3-D surface plot. The contrast as a function of LC layer thickness was obtained. These contrasts are plotted as a function of  $\Delta n \cdot d / \lambda$  (birefringence  $\Delta n$ , thickness  $d$ , wavelength  $\lambda$ ) in Figure 30. As  $\Delta n \cdot d / \lambda$  increases the contrast rapidly decreases. A maximum contrast of 89 was obtained, corresponding to a  $\Delta n \cdot d / \lambda = 0.25$ ,  $d = 2 \mu\text{m}$ ,  $\theta = 81^\circ$ ,  $\phi = -11^\circ$ . The corresponding luminous reflectance curves for  $\phi = -11^\circ$  and  $\phi = 349^\circ$  twist states are given in Figure 31. The  $(\phi + 360^\circ)$  high twist state gave a higher luminance than the  $(\phi - 360^\circ)$  high twist state.

Further improvements are possible by varying the retardation (thickness) of the fixed half-wave retarder and repeating this exercise.

#### Embodiment 7

*Two half-wave ( $\lambda/2$ ) retarders + ( $3\lambda/4$ ) LC - untwisted dark state  $\phi = 0^\circ$ .*

Two half-wave retarders ( $\Delta n \cdot d = 270$ ) placed at  $15^\circ$  and  $-15^\circ$  to the transmission axis of the polariser with a  $6 \mu\text{m}$  LC layer at  $75^\circ$ , as shown in Figure 32. The untwisted state corresponds to the dark state and the high twist state gives the bright state. The resulting dark and bright states are not very achromatic, see reflectance curves plotted in Figure 33, leading to a low contrast of 20. Dark state has a short 500-550nm wavelength range. The luminous reflectance curves (e.g.  $0^\circ$  and  $-360^\circ$  twist states) are very chromatic which may be usable as a two



colour display (achromatic dark state and coloured bright state).

Embodiment 7 can be seen as belonging to a more general case:

$(\lambda/2) @ -15^\circ + [(\lambda/4)+x] @ -15^\circ + [(\lambda/2)+x] @ -75^\circ$  where  $x$  lies between 0 &  $\lambda/4$ .

Embodiment 8

Two half-wave  $(\lambda/2)$  retarders +  $(\lambda/4)$  LC - untwisted dark state  $\phi=0^\circ$ .

The two half-wave retarders ( $\Delta n \cdot d = 270$ ) are at  $6.9^\circ$  and  $34.5^\circ$  to the transmission axis of the polariser, as shown in Figure 34. An untwisted,  $2\mu\text{m}$  LC layer, at  $100^\circ$  to the transmission axis of the polariser, provides a good achromatic dark state (minimum reflectance over  $\sim 180\text{nm}$  wide wavelength range), with the exception that at very low wavelengths the dark state becomes poor, see Figure 35. The high twist ( $\pm 360^\circ$ ) state in turn gives a good bright state (though chromatic in behaviour) which leads to a contrast of 89. The dark state may be improved (possibly increasing the contrast) by decreasing the thickness of the retarders and LC layer.

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Additionally, increasing the thickness of the LC layer and determining for that thickness the optimum ( $\theta$  orientation and  $\phi$  twist of LC layer) configuration as described in Embodiment 6, other high contrasts may be found. It could also be possible to increase the thickness of the LC layer by using the LC as one of the  $(\lambda/2)$  elements instead of the  $(\lambda/4)$  element, though this would require an internal retarder which could be

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fabricated by a reactive mesogen layer as described in Embodiment 3.

*Embodiment 9*

- 5 A ( $23\lambda/72$ ) and ( $\lambda/2$ ) retarder + LC ( $23\lambda/72$ ) - untwisted dark state  $\phi=0^\circ$ .

10 A  $23\lambda/72$  (@550nm) retarder placed at  $14.25^\circ$  to the transmission axis of the polariser followed by a half-wave ( $\Delta n \cdot d = 270$ ) retarder at  $84.5^\circ$ . The LC is oriented at  $14.25^\circ$  and has a retardation of  $\sim 23\lambda/72$  ( $d = 2.56\mu\text{m}$ ). Figure 36 gives a schematic representation of this configuration. The dark state is given by the untwisted state  $\phi=0^\circ$ . The bright state is obtained by the high twisted ( $\pm 360^\circ$ ) state, 15 though the undesired  $\pm 180^\circ$  twist state gave a higher luminance than the  $\pm 360^\circ$  twist state, as can be seen in Figure 37. A contrast of 55 is obtained.

20 The thickness of the LC layer could be increased by using the LC as the ( $\lambda/2$ ) element instead of the ( $23\lambda/72$ ) element, though this again would require an internal retarder.

*Embodiment 10*

- 25 Achromatic configuration + LC: ( $\lambda/2$ ) retarder + ( $\lambda/4$ ) retarder + ( $\lambda/4$ ) LC layer.

30 This configuration is different to all the previous configurations discussed because the fixed retarder(s) provide the dark state and the LC is used to switch their effect on and off. Therefore, the high twist state gives the dark state and the low twist state gives the bright state.

The half-wave ( $\Delta n \cdot d = 270$ ) retarder is at  $15^\circ$  to the transmission axis of the polariser and the quarter-wave ( $\Delta n \cdot d = 132.5$ ) retarder and LC layer are both at  $75^\circ$ , as shown in Figure 38. A  $2\mu\text{m}$  thick LC layer was used and this gave a contrast of 96 with a good dark state that is reasonably achromatic, except at low wavelengths. Luminous reflectance curves are shown in Figure 39, it can be observed that the high twist ( $\pm 360^\circ$ ) states gave very similar dark states.

*Embodiment 11*

*Achromatic configuration + LC (varying the LC layer thickness) - high twist dark state.*

This configuration utilises the same half-wave/quarter-wave retarder configuration used in Embodiment 10: the LC switches the achromatic quarter-wave configuration on and off. The LC configuration ( $\theta$  and  $\phi$ ) which gave the best dark state for a given LC layer thickness was found. Repeating over a range of LC layer thickness' and therefore  $\Delta n d / \lambda$  as done in Embodiment 6. The bright state was given by the corresponding low twist state. The general configuration is represented in Figure 40. The contrasts determined were plotted as a function of  $\Delta n d / \lambda$  in Figure 41. Once again, two contrast maxima are found. The highest occurs at  $\Delta n d / \lambda = 0.25$  ( $d = 2\mu\text{m}$ ,  $\theta = -70^\circ$ ,  $\phi = -15^\circ$ ) and gives a contrast of 133. Its luminous reflectance curves are plotted in Figure 42. As can be seen, a very good dark state (very achromatic) and a very reasonable bright state are obtained, though both are poor at low wavelengths. The second maxima occurs at  $\Delta n d / \lambda = 0.72$  ( $d = 5.781\mu\text{m}$ ,  $\theta = 3^\circ$ ,  $\phi = -24^\circ$ ), contrast of 106.

The dark state is reasonably good but the bright state is very chromatic, see its' reflectance curves in Figure 43.

- 5           An example of one of the poorer contrasts ( $CR=23$ ) obtained (thickness of  $4.3\mu m$ ,  $\theta=0^\circ$ ,  $\phi=-15^\circ$ ) is also included. Its reflectance curves, Figure 44, show a reasonable dark state with a very poor bright state.

10       INDUSTRIAL APPLICABILITY

- According to the invention, high contrast is obtained in reflection in various BTN configurations by means of achromatic dark states (dark over a wide range of wavelengths, preferably covering all the visible range) which switch to good bright states.
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